High-Fidelity Probabilistic Collapse Assessment of Tall Steel Buildings under Extreme Winds

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ABSTRACT:
To further the knowledge required to implement performance-based wind engineering (PBWE), this study proposes a general framework for the probabilistic collapse assessment of tall steel buildings based on an uncertain fiber-based nonlinear modeling environment driven by wind tunnel informed stochastic wind loads calibrated to site-specific wind data. The fiber-based nonlinear modeling environment provides a means to explicitly simulate potential collapse from yielding, buckling, low-cycle fatigue, and fatigue-induced fiber fracture. For efficient estimation of rare events, e.g. collapse, the modeling environment is housed in a stochastic simulation framework that makes use of an Optimal Stratified-sampling based Monte Carlo Simulation (OSMCS) scheme that minimizes the variance of a target failure probability of interest. The effectiveness of the proposed framework is demonstrated on a 45-story steel braced archetype building.

Keywords: Reliability analysis, Nonlinear modeling, Probabilistic collapse assessment, Monte Carlo methods

1. INTRODUCTION

To cater to the growing interest to migrate from current design practices for wind that are based on elastic analysis and equivalent static loads to performance-based design techniques, there is a need for general performance-based wind engineering (PBWE) frameworks that are applicable to a wide range of structures. Previous studies have proposed frameworks based on incremental dynamic analysis (e.g., Judd and Charney, 2015), nonlinear time history analysis (NLTHA), and dynamic shakedown (Chuang and Spence, 2020), notably, using a range of complexity of numerical structural models to investigate performance under service loads, at first yield, and near collapse. However, they have not explicitly addressed the pressing need to efficiently estimate collapse-level reliability in the face of high-dimensional uncertainties and investigate the relative distance between the reliabilities associated with different limit states of interest. To address these knowledge gaps, a fully probabilistic collapse assessment framework is proposed in this work for assessing collapse probabilities/reliabilities through the adoption of an uncertain high-fidelity fiber-based structural modeling environment that is embedded in an efficient Monte Carlo Simulation (MCS) framework, referred to as the Optimal Stratified-sampling based Monte Carlo Simulation (OSMCS) scheme. The proposed framework is illustrated on a 2D braced steel frame extracted from a fully 3D archetype building.

2. RELIABILITY ASSESSMENT FRAMEWORK

Dynamic analysis of a structural system with material and geometric nonlinearities included, requires solving the following equation of motion:

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$$\mathbf{M}\ddot{\boldsymbol{u}}(t) + \boldsymbol{f}_D\big(\boldsymbol{u}(t), \dot{\boldsymbol{u}}(t)\big) + \boldsymbol{f}_r\big(\boldsymbol{u}(t)\big) = \boldsymbol{f}_{\bar{v}_H, \alpha}(t) \tag{1}$$

where $\boldsymbol{u}$, $\dot{\boldsymbol{u}}$ and $\ddot{\boldsymbol{u}}$ are the vector of displacements, velocities and accelerations at the discretized degrees of freedom at any time t and $\mathbf{M}$ is the mass matrix, $\boldsymbol{f}_D$ and $\boldsymbol{f}_r$ are the vectors of damping and restoring forces that have nonlinear dependence on $\boldsymbol{u}$, and $\boldsymbol{f}_{\bar{v}_H, \alpha}$ is the stochastic wind load vector for wind direction α and hourly mean wind speed at the building top $\bar{v}_H$. A high-fidelity fiber-based modeling environment with the corotational formulation is used to estimate $\boldsymbol{f}_D$ and $\boldsymbol{f}_r$, such that they account for behaviour such as stiffness degradation, fatigue-induced fiber damage, progressive plastification, and damping. A Rayleigh damping model, as recommended for use in nonlinear analysis (Charney, 2008), is adopted. Each compression member is modeled using two inelastic elements with random initial camber to trigger flexural buckling. The Menegotto-Pinto material model is adopted to simulate the cyclic behaviour of steel along with low-cycle fatigue and potential fiber fracture (Karamanci and Lignos, 2014).

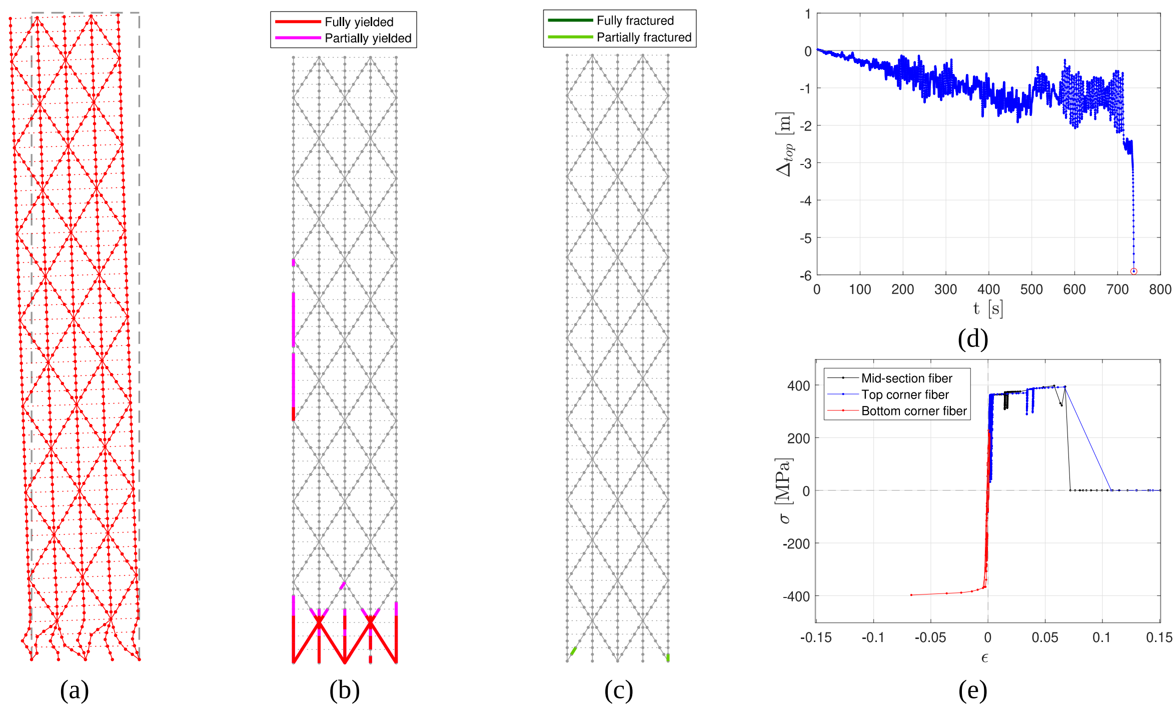

Figure 1. Illustration of a collapse scenario: (a) Deformed shape at collapse; (b) Partially (fiber level) and fully (sectional) yielded components; (c) Partially (fiber level) and fully (sectional) fractured components; (d) Roof displacement history; (e) Stress-strain history of fibers in an end section of the partially fractured base column

The stochastic wind load vector, $\boldsymbol{f}_{\bar{v}_H, \alpha}$, is generated using a peak elastic load effect-based hazard curve and spectral proper-orthogonal decomposition (SPOD) based stochastic wind load model. The hazard curve uses a simplified elastic model, and site-specific wind data to jointly model $\bar{v}_H$ and α. A kernel density copula is utilized to jointly model the wind speed and direction (Ouyang and Spence, 2020). The SPOD model captures complex aerodynamic phenomena on account of calibration to the cross-power spectral density matrix of the building-specific aerodynamic loads, as informed by wind tunnel data. A full range of code-consistent uncertainties in the structure (e.g., damping, material properties, initial imperfections) and loads (e.g., gravity loads, uncertainties associated with the use of wind tunnel data) are propagated through the system using limited sample sets. This is achieved using the OSMCS scheme, a modified version of the conditional simulation scheme (Ouyang and Spence, 2020), in which MCS samples are optimally allocated to wind speed subevents to minimize the estimator variance.

3. CASE STUDY

A 2D steel braced frame extracted from a 45-story archetype building assumed to be located in New York City is used to demonstrate the proposed framework. To implement OSMCS, the hazard curve was partitioned into 10 mutually exclusive and collectively exhaustive wind speed intervals and a total of 1000 MCS samples were utilized. The optimal allocation was based on variance minimization for collapse probability. Fig. 1 shows a collapse mechanism together with component yielding, fracture, displacement history, and stress-strain histories illustrating fiber fracture. Table 1 summarises the failure probabilities expressed as annual exceedance probabilities (AEP) and 50-year reliability indices, β_{50}, for four limit states of interest. The efficiency of the OSMCS scheme in comparison to crude MCS is also shown. From Table 1, it is clear that: 1) the probability of component failure, in terms of fracture, is significantly lower than the probability of component-level first yield; and 2) the probability of system collapse is not significantly lower than the probability of component-level first yield, illustrating the importance of explicit collapse analysis if wind excited structures are to be allowed to experience inelasticity during design.

Table 1. Failure probabilities and 50-yr reliability indices

Limit State	System Collapse	System First Yield	Component First Yield	Component Fracture
AEP	6.83×10^{-5}	7.04×10^{-4}	6.58×10^{-4}	7.13×10^{-6}
COV (MCS)	211%	66%	68%	654%
COV (OSMCS)	13%	36%	38%	39%
β_{50}	2.71	1.82	1.85	3.38

4. CONCLUSION

A general framework for high-fidelity probabilistic collapse assessment of steel structures subjected to extreme wind loads was developed. The need to explicitly evaluate collapse if inelasticity is to be allowed in design was illustrated.

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REFERENCES

Charney, F.A., 2008. Unintended consequences of modeling damping in structures. Journal of structural engineering, 134(4), pp.581-592.

Chuang, W.C., and Spence, S.M., 2020. Probabilistic performance assessment of inelastic wind excited structures within the setting of distributed plasticity. Structural Safety, 84, p.101923.

Judd, J.P. and Charney, F.A., 2015. Inelastic behavior and collapse risk for buildings subjected to wind loads. In Structures Congress 2015 (pp. 2483-2496).

Karamanci, E. and Lignos, D.G., 2014. Computational approach for collapse assessment of concentrically braced frames in seismic regions. Journal of Structural Engineering, 140(8), p.A4014019.

Ouyang, Z. and Spence, S.M., 2020. A Performance-Based Wind Engineering Framework for Envelope Systems of Engineered Buildings Subject to Directional Wind and Rain Hazards. Journal of Structural Engineering, 146(5), p.04020049.